LOOKING FOR LEPTONIC CP VIOLATION WITH NEUTRINOS*

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I discuss some theoretical aspects of how to observe leptonic CP violation. It is divided into two parts, one for CP violation due to Majorana, and the other more conventional leptonic Kobayashi-Maskawa (KM) phases. In the first part, I estimate the effect of Majorana phase to observable of neutrinoless double beta decay experiments by paying a careful attention to the definition of the atmospheric scale Δm^2. In the second part, I discuss Tokai-to-Kamioka-Korea two detector complex which receives neutrino superbeam from J-PARC as a concrete setting for discovering CP violation due to the KM phase, as well as resolving mass hierarchy and the θ_{23} octant degeneracy. A cautionary remark is also given on comparison between various projects aiming at exploring CP violation and the mass hierarchy.

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1. Introduction

On the occasion of 50 years anniversary of discovery of parity violation, this conference is focused on the problem of fundamental symmetries. Leptonic CP violation is an important and indispensable element of our understanding of not only neutrinos but also particle physics itself. It is because neutrino masses and the flavor mixing discovered by the atmospheric [1], the solar [2], and the reactor [3] experiments constitute so far the unique evidence for physics beyond the Standard Model. Moreover, it may be the key to understand the baryon number asymmetry in the universe [4].

CP violation in the lepton sector can be classified into the two categories; the one due to possible Majorana phase [5] and to the conventional Kobayashi-Maskawa (KM) phase [6] in the lepton flavor mixing matrix, the MNS matrix [7]. While it is generally believed that CP violation of the

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latter type exists in nature, CP violation of the former type requires the existence of Majorana mass term. But, once neutrinoless (0ν) double beta decay is observed, the Majorana CP violation must exist because of the general theorem [8]; presence of the 0ν double beta decay matrix elements implies the existence of the Majorana mass term irrespective of the origin of the 0ν double beta decay. Furthermore, there is a general argument [9] which states that under the assumption of Standard Model, neutrinos must be Majorana particles to explain the baryon asymmetry in the universe.

Despite that there is little doubt on the importance of uncovering leptonic CP violation, executing the task is extremely difficult. Therefore, the question of "how to discover CP violation" is worth to be discussed even more extensively than the level it has been done. In the following, I want to discuss some aspects of measuring CP violation due to the Majorana and the KM type phases under the hope that accumulating such discussions eventually leads to the feasible and promising experimental ideas.

2. Measuring the Majorana phase

Let us start with the discussion of the Majorana phase. Practically, 0ν double beta decay is the only known experimentally feasible way to identify the Majorana nature of neutrinos and measure the value of Majorana phase through its CP conserving effect [10] in the rate. For recent reviews of 0ν double beta decay, see e.g. [11].[1]

2.1. Do 0ν double beta decay experiments distinguish the mass hierarchy?

In Fig. 1 plotted is the 0ν double beta decay observable $\langle m \rangle_{\beta\beta}$ as a function of the lowest neutrino mass (left panel) and of sum of neutrino masses, $\Sigma \equiv \sum_{i=1}^{3} m_i$ (right panel). It appears that because of the clear distinction between the normal and the inverted mass hierarchies in the left figure the double beta decay experiments can discriminate between the hierarchies. However, the picture changes completely if one looks at the right panel of Fig. 1. Therefore, as far as Σ is the only additional observable, it can be done only in a tiny region, unfortunately.

Therefore, I would like to take the attitude that the neutrino mass hierarchy will be determined by future accelerator LBL experiments, and consider below the implication of possible future observation of 0ν double

[1] Apart from the possibility of observing Majorana CP violation the 0ν double beta decay is a rich source of informations. For example, if neutrinos are the Majorana particles and the degenerate mass spectrum is the case, it was shown that the small angle MSW solution is disfavored [12]. If the degenerate mass Majorana neutrinos exist, as claimed by Klapdor *et al.* [13], it might have been one of the first indications that the solar mixing angle is large. Of course, the claim in [13] has to be verified by the independent measurement.

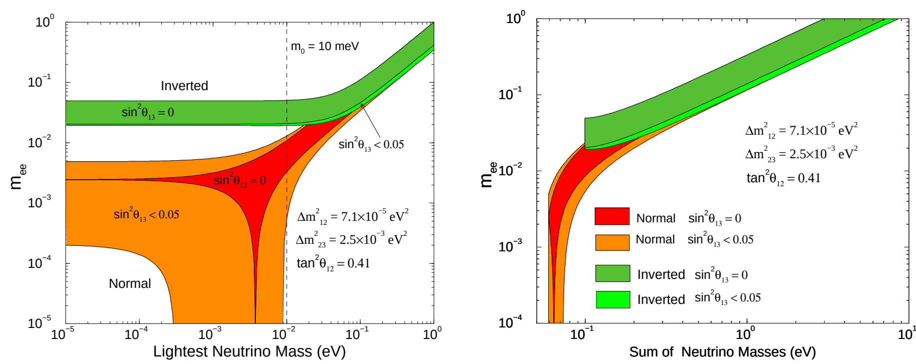

Fig. 1. The 0ν double beta decay observable $m_{ee} \equiv \langle m_{\beta\beta}\rangle$ in our notation, is plotted as a function of the lowest neutrino mass (left panel) and of sum of neutrino masses, $\Sigma \equiv \sum_{i=1}^{3} m_i$ (right panel). The figures are by courtesy of Hiroshi Nunokawa.

beta decay events in the context of Majorana CP violation. (See Sec. 3.2 for an example of such LBL projects.)

2.2. Analytic estimate of the effect of Majorana phase

With use of the standard notation of the MNS matrix [14], the observable in neutrinoless double beta decay experiments can be expressed as

$$\begin{aligned} \langle m\rangle_{\beta\beta} &= \left| m_1 c_{12}^2 c_{13}^2 e^{i\phi_1} + m_2 s_{12}^2 c_{13}^2 e^{+i\alpha} + m_3 s_{13}^2 e^{-i\alpha} \right|, \\ &= \left| m_1 c_{12}^2 c_{13}^2 e^{+i\beta} + m_2 s_{12}^2 c_{13}^2 e^{-i\beta} + m_3 s_{13}^2 e^{i\phi_3} \right|, \end{aligned} \quad (1)$$

where m_i (i=1, 2, 3) denote neutrino mass eigenvalues. The first and the second lines of (1) are for the normal ($\Delta m^2_{32} > 0$) and the inverted ($\Delta m^2_{32} < 0$) mass hierarchies, respectively, and the Majorana phases α, β etc. are parametrized in (1) in a convenient way for our later discussions [12]. We use the convention that m_3 is the largest (smallest) mass in the normal (inverted) mass hierarchy.

To express the mass eigenvalues in terms of observable Δm^2's we pay careful attention to the fact that neither $|\Delta m^2_{32}|$ nor $|\Delta m^2_{31}|$ (with definition of $\Delta m^2_{ij} \equiv m_i^2 - m_j^2$) is the observable quantity. In ν_μ disappearance measurement it is [15][2]

$$\Delta m^2_{\mu\mu} = s_{12}^2 |\Delta m^2_{31}| + c_{12}^2 |\Delta m^2_{32}| + \cos\delta \sin 2\theta_{12} \tan\theta_{23} s_{13} \Delta m^2_{21}. \quad (2)$$

[2] If we use ν_e disappearance measurement it is given by $\Delta m^2_{ee} = c_{12}^2|\Delta m^2_{31}| + s_{12}^2|\Delta m^2_{32}|$ [15]. These expressions are shown to be of key importance in estimating sensitivities to mass hierarchy resolution by the disappearance methods [16].

Solving (2) we obtain for the normal mass hierarchy ($\Delta m^2_{32} > 0$, $m_1 = m_l$);

$$\begin{aligned} m_3^2 &= \Delta m^2_{\mu\mu}\left[1+\epsilon\left\{c_{12}^2 - \cos\delta\sin 2\theta_{12}\tan\theta_{23}s_{13}\right\}+\kappa\right], \\ m_2^2 &= \Delta m^2_{21}\left[1+\frac{\kappa}{\epsilon}\right] \end{aligned} \tag{3}$$

and for the inverted mass hierarchy ($\Delta m^2_{32} < 0$, $m_3 = m_l$);

$$\begin{aligned} m_2^2 &= \Delta m^2_{\mu\mu}\left[1+\epsilon\left\{s_{12}^2 - \cos\delta\sin 2\theta_{12}\tan\theta_{23}s_{13}\right\}+\kappa\right], \\ m_1^2 &= \Delta m^2_{\mu\mu}\left[1-\epsilon\left\{c_{12}^2 + \cos\delta\sin 2\theta_{12}\tan\theta_{23}s_{13}\right\}+\kappa\right], \end{aligned} \tag{4}$$

where $\epsilon \equiv \Delta m^2_{21}/\Delta m^2_{\mu\mu} \simeq 0.032$ and $\kappa \equiv m_\ell^2/\Delta m^2_{\mu\mu}$.

2.3. Observable under the approximation of ignoring lowest ν mass

For simplicity, we restrict our discussion to the case m_ℓ can be ignored compared to other two mass eigenvalues. Then, we obtain the expression of $\langle m\rangle^2_{\beta\beta}$ for the normal mass hierarchy as

$$\frac{\langle m\rangle^2_{\beta\beta}}{\Delta m^2_{21}} = s_{12}^4 c_{13}^4 + \frac{s_{13}^4}{\epsilon} + 2\sqrt{\frac{s_{13}^4}{\epsilon}}s_{12}^2c_{13}^2\cos 2\alpha + \sqrt{\epsilon}s_{13}^2c_{12}^2s_{12}^2\cos 2\alpha, \tag{5}$$

where we have ignored the terms of order ϵ^2, s_{13}^4 which are not enhanced by inverse power of ϵ, and $\sqrt{\epsilon}s_{13}^3$. Notice that $\langle m\rangle^2_{\beta\beta}$ is naturally of order $\sim \Delta m^2_{21}$ in the normal hierarchy. In the inverted hierarchy, it is of the order of Δm^2_{atm} and takes the form

$$\begin{aligned} \frac{\langle m\rangle^2_{\beta\beta}}{\Delta m^2_{\mu\mu}} &= c_{13}^4\left[1-\sin^2 2\theta_{12}\sin^2\beta - \epsilon\left\{1-\frac{1}{2}\sin^2 2\theta_{12}\sin^2\beta\right\}\right. \\ &\qquad \left. -\epsilon\cos\delta\sin 2\theta_{12}\tan\theta_{23}s_{13}\left\{1-\sin^2 2\theta_{12}\sin^2\beta\right\}\right], \end{aligned} \tag{6}$$

Here, we notice that the difference between our results in (5) and (6) and the ones which would be obtained if we use the naive definition $\Delta m^2_{atm} = \Delta m^2_{32}$ is very small. In the normal hierarchy case, it is of the order of the last term in (5) (coefficient doubled) which is of order $\sqrt{\epsilon}s_{13}^2 \leq 5\times 10^{-3}$. In the inverted hierarchy case, the difference is in order $\epsilon \simeq 0.03$ terms; The second line in (6) is of course missing and unity in the curly bracket in the first line is replaced by s_{12}^2. Therefore, the careful definition of the atmospheric Δm^2 [15] does not appear to produce detectable difference in the 0ν double beta decay observable. This feature seems to be generic and is true without approximation of ignoring the lowest neutrino mass.

We estimate how large is the effect of the Majorana phase in (5) and (6). To make a fair comparison between the normal and the inverted hierarchy cases we compute the ratio of the coefficient of $\cos 2\alpha$ (or $\cos 2\beta$) to the phase independent piece, B/A in $\langle m \rangle^2_{\beta\beta} = A + B \cos 2\alpha$. (Note that the experimental observable is the square of $\langle m \rangle_{\beta\beta}$.) The results of the ratios are about $0.72 \times (s^2_{13}/0.025)$ and 0.79 independent of s_{13} in the normal and the inverted mass hierarchies, respectively. Therefore, the effect of the Majorana phase is large in both hierarchies (for the normal hierarchy if s^2_{13} is large) and should be observed if the experiments are accurate enough and the uncertainty of the nuclear matrix elements can be solved. It is the challenge to the next generation double beta decay experiments, whose partial list is in [17], to reach the sensitivity of this level to observe the Majorana phase. A promising idea for resolving the problem (or at least much improving the situation) of uncertainty of the nuclear matrix elements is proposed [18].

What about the uncertainties which may be caused by other mixing parameters involved in (5) and (6). The error of s^2_{12} can be controlled down to about a few % if low energy *pp* neutrino is accurately measured [19], and/or to $\simeq$2% if a dedicated reactor [20] or the Mössbauer-type measurement [21] is executed. The error for $\sin^2 2\theta_{12}$ is even smaller by a factor of $\sim$2. Therefore, there is little additional uncertainty in the inverted hierarchy case. In the normal hierarchy case the major uncertainty would come from the error of s^2_{13} measurement on which we do not yet have definitive perspective.

Though my analysis in this paper is rather qualitative I hope it illuminates the main point of the more quantitative analysis. Examples of recent analysis of 0ν double beta decay, in particular on the possibility of observing the Majorana phase see e.g. [22].

3. Measuring the leptonic Kobayashi-Maskawa phase

3.1. General comments

Probably the most popular way of measuring CP violation of the KM type is the long-baseline (LBL) accelerator neutrino experiments. Since the appearance oscillation probabilities of $\nu_\mu \to \nu_e$ and the one with their anti-neutrinos have different dependence on CP phase δ, $P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = 16 c_{12} s_{12} c_{23} s_{23} c^2_{13} s_{13} \Pi_{i,j=\text{cyclic}} \sin\left(\frac{\Delta m^2_{ij} L}{4E}\right)$ in vacuum, one can in principle detect the effect of CP violation by comparing ν_e ($\bar{\nu}_e$) yields in ν_μ ($\bar{\nu}_\mu$) beam exposure.

Unfortunately, it is not the end of the story. The earth matter effect inevitably comes in as a contamination in CP phase measurement, because the earth matter is CP asymmetric. The interplay between the genuine CP phase effect and the matter effect is extensively discussed in the literature.

A few early ones are in [23, 24, 25]. One way of dealing with the issue of matter effect contamination is to carry out the experiments in a near vacuum setting, low energy conventional superbeam to search for CP violation [26]. Concrete examples of such setting include the ones described in [27, 28]. Another way to deal with the problem is to perform *in situ* measurement of the matter effect in the experiments, as emphasized in [29] and illustrated for neutrino factory in [30, 31]. Effects of errors in the matter density on the CP sensitivity in neutrino factory is discussed e.g., in [32].

Nonetheless, it is important to recognize that the matter contamination in CP violation measurement is *not* entirely a bad news. Namely, one can resolve the neutrino mass hierarchy by utilizing the interference between the vacuum and the matter effects. I think that these discussions make it clear that we must invent a consistent experimental framework in which one can achieve simultaneous determination of CP phase δ and the neutrino mass hierarchy. Furthermore, it became the *necessity* when the problem of parameter degeneracy, the ambiguity due to multiple solutions of lepton mixing parameters, was uncovered [33, 34, 35]. For its various aspects, see [36, 37, 38]. Unless we can formulate the way of how to resolve it and give reliable estimation of the sensitivity it would be difficult to convince people of the value of such an inevitably expensive project.

3.2. T2KK; Tokai-to-Kamioka-Korea two detector complex

I want to describe our proposal which we believe to possess the required properties as described above. It is now called T2KK, acronym of the Tokai-to-Kamioka-Korea identical two detector complex [39, 40]. See [41] for more global overview of the project, in particular the latest status as well as atmosphere in the initial stage.

The basic idea of T2KK setting is the comparison between the yields at the two detectors [42], one in Kamioka (295 km) and the other in Korea (1050 km) whose former (latter) location is near the first (second) oscillation maximum. As indicated in Fig. 2 in the form of $P(\nu_\mu \to \nu_e)$-$P(\bar{\nu}_\mu \to \bar{\nu}_e)$ bi-probability plot [34] the behavior of the appearance oscillation probabilities in Kamioka and Korea are vastly different. It will allow us to resolve the intrinsic [33] and the sign-Δm^2_{31} [34] degeneracies to determine CP phase δ and the mass hierarchy.

In Fig. 3 presented are the results of the sensitivities to mass hierarchy resolution and detection of CP violation obtained in [39]. As indicated in the figure, the T2KK setting has potential of discovering KM type leptonic CP violation and at the same time resolve the neutrino mass hierarchy if θ_{13} is in the region of sensitivities possessed by the next generation reactor [43] and the accelerator LBL experiments [28, 44].

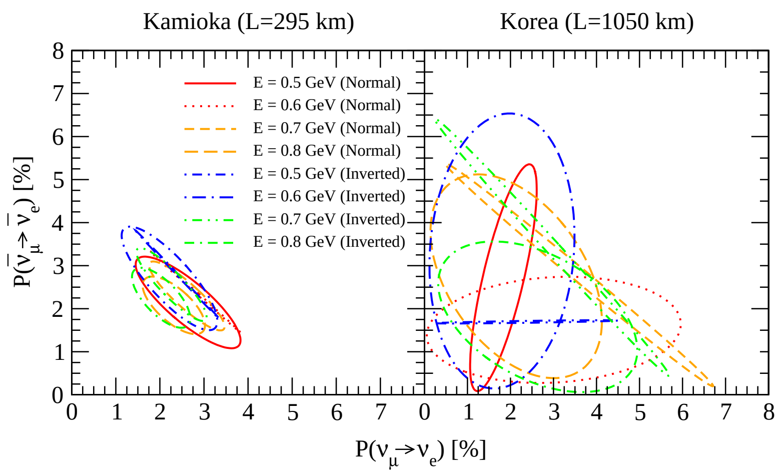

Fig. 2. Energy dependences of the oscillation probabilities for $\sin^2 2\theta_{13} = 0.05$ are represented by plotting ellipses (which results as δ is varied from 0 to 2π) in bi-probability space for various neutrino energies from 0.5 to 0.8 GeV. The left and the right panels are for detectors in Kamioka and in Korea, respectively. The ellipses in upper 4 symbols (warm colors) indicate the ones of normal mass hierarchy ($\Delta m^2_{31} > 0$) and the one of lower 4 symbols (cold colors) the ones of inverted mass hierarchy ($\Delta m^2_{31} < 0$). The figure is taken from [39].

I also note that T2KK has potential of lifting the θ_{23} octant degeneracy [40] by detecting the solar scale oscillation effect, as proposed for atmospheric neutrino observation [45]. The sensitivities to the octant ambiguity resolution is better (worse) compared to the best thinkable sensitivity achievable by the reactor-accelerator combined method [46] in a region $\sin^2 2\theta_{13}$ smaller (greater) than 0.05-0.06. These values are based on the sensitivity estimated in [40] and [47]. To sum up, T2KK will have an *in situ* potential of resolving the total eight-fold parameter degeneracy, thereby fulfilling the required qualification as a candidate for future LBL neutrino oscillation experiments for determining lepton mixing parameters.

Since most of the future LBL projects are equipped with large detectors they automatically possess the potential of resolving the θ_{23} octant degeneracy by atmospheric neutrino observation. The point is, however, that by having an *in situ* potential of resolving the degeneracy T2KK can use such the additional capability as a consistency check of the results, guaranteeing the desirable “redundancy”. Since the systematic errors involved are quite different in both methods I believe that such redundancy must be retained to make the measurement robust ones. The similar statement may apply to the mass hierarchy resolution.

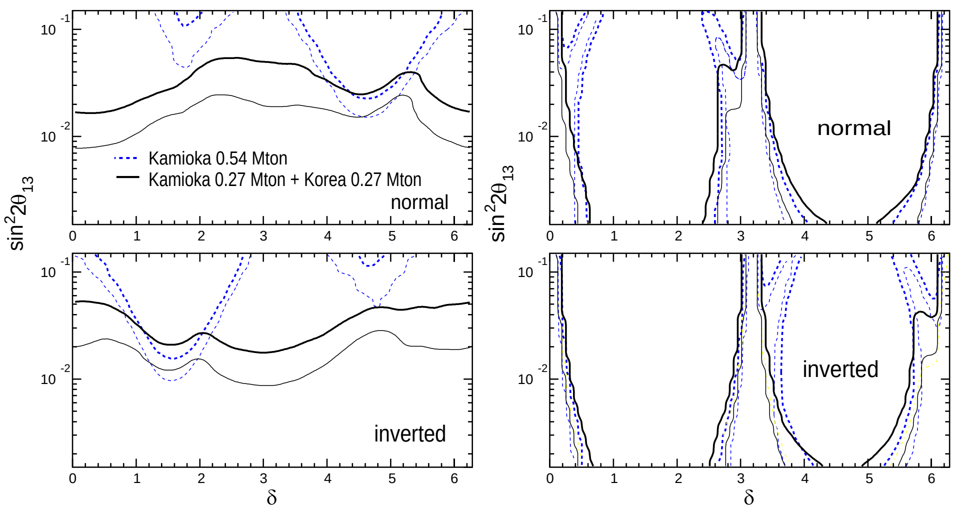

Fig. 3. Presented are the sensitivities to the mass hierarchy determination (left panel) and CP violation (right panel) at 2σ(thin lines) and 3σ (thick lines) CL. The standard deviation is defined with 1 degree of freedom (DOF). The black solid lines are for the T2KK setting while the blue dotted lines are for the T2K II setting. θ_{23} is taken to be maximal. The top and bottom panels are for the normal and the inverted mass hierarchies, respectively. The results is from [39].

3.3. Remarks on comparison between the projects

Some people tries to compare the sensitivities to the mass hierarchy resolution and CP violation possessed by various projects proposed [48]. Though important I would like to make a cautionary remark on such comparison between projects which use water Cherenkov detectors. It is known that the issue of background rejection at high energies becomes highly nontrivial in the detector. Therefore, if one wants to compare two settings which does and does not require the special care for background rejection at high energies, this problem has to be settled first in a convincing way.

As an example I show in Fig. 4 the sensitivity estimate done by Dufour [49] for the VLBL project with the Ferimilab-Homestake baseline (1300 km) If one compares Fig. 4 to Fig. 11 in [50], one notices that the sensitivity reach for the mass hierarchy obtained by Dufour is worse than that in [50] despite usage of more aggressive setting of beam power of 2 MW for 5 years running for both neutrinos and antineutrinos. For more details, see [49]. It should be noticed that while Fig. 4 contains a comparison between the discovery potentials of the two projects, T2KK and the VLBL project, the settings of the both experiments (beam power etc.) are rather different.

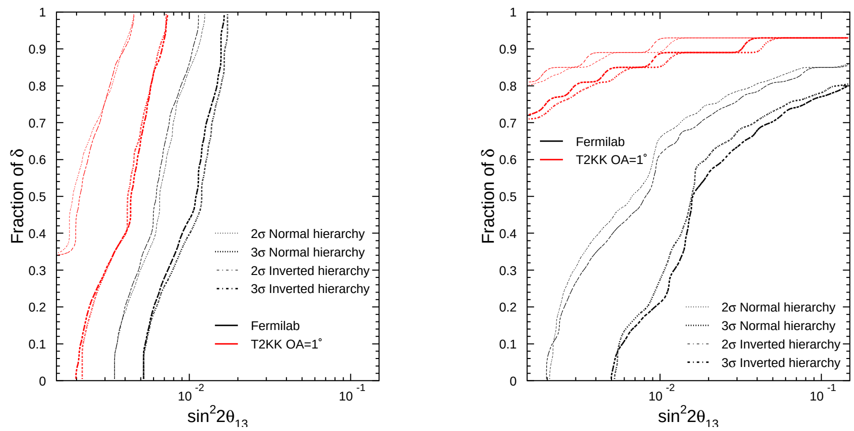

Fig. 4. Fractional coverage of CP phase δ in which there are sensitivities to the mass hierarchy determination (left panel) and CP violation (right panel) by Fermilab-Homestake VLBL project (black curves) and T2KK with Korean detector at 1 degree off-axis angle (red curves) [49]. The thick (thin) lines are at 3σ (2σ) CL. The standard deviation is defined with 1 DOF. θ_{23} is taken to be maximal. The dotted and the dash-dotted lines are for the normal and the inverted mass hierarchies, respectively. The figure is by courtesy of Fanny Dufour.

4. Concluding remarks

In this talk, I tried to describe some aspects of the problem of how to detect CP violation due to both the Majorana and the KM phases in the lepton mixing. Though they are extremely difficult to carry out, the implications of the detection are so great that it is worth to continue to think about them. I thank the organizers for invitation to the conference in such a scenic place, Mazurian Lakes, which gave me the chance of revisiting the issue of Majorana phase in the 0ν double beta decay.

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